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Koumura et al.

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[54] VARIFOCAL LENS

[75] Inventors: Tukasa Koumura, Toyota; Michio Hisanaga, Nagoya; Tadashi Hattori, Okazaki, all of Japan

[73] Assignee: Nippondenso Co., Ltd., Kariya, Japan

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[30] Foreign Application Priority Data

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[51] Int. Cl.[6] G02B 1/06; G02B 3/12; G02B 15/14

[52] U.S. Cl. 359/666; 359/676

[58] Field of Search 359/666, 676

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Primary Examiner—Georgia Y. Epps
Assistant Examiner—Jacqueline M. Steady
Attorney, Agent, or Firm—Cushman, Darby & Cushman

[57] ABSTRACT

A varifocal lens whose variable focal length can be controlled by, for example, an electric signal, and suitable for use in bar code readers, etc. A varifocal lens comprises a first pressure chamber defined between a glass substrate and a transparent elastic film. The transparent elastic film is faced to the surface of the planar glass substrate having parallel surfaces with a spacer incorporated therebetween to provide the first pressure chamber. A pump is provided adjacent to the first pressure chamber via a communicating path for charging an operating liquid to the first pressure chamber from a second pressure chamber of the pump by electrically deforming the transparent elastic film to form a lens having a variable focal length. The transparent elastic film has a film thickness distribution as such to provide a spherical plane in the central portion thereof and a third order curved surface in the periphery thereof. In this manner, a lens free of aberration can be obtained when a liquid is fed into the first pressure chamber to form a spherical plane.

14 Claims, 4 Drawing Sheets

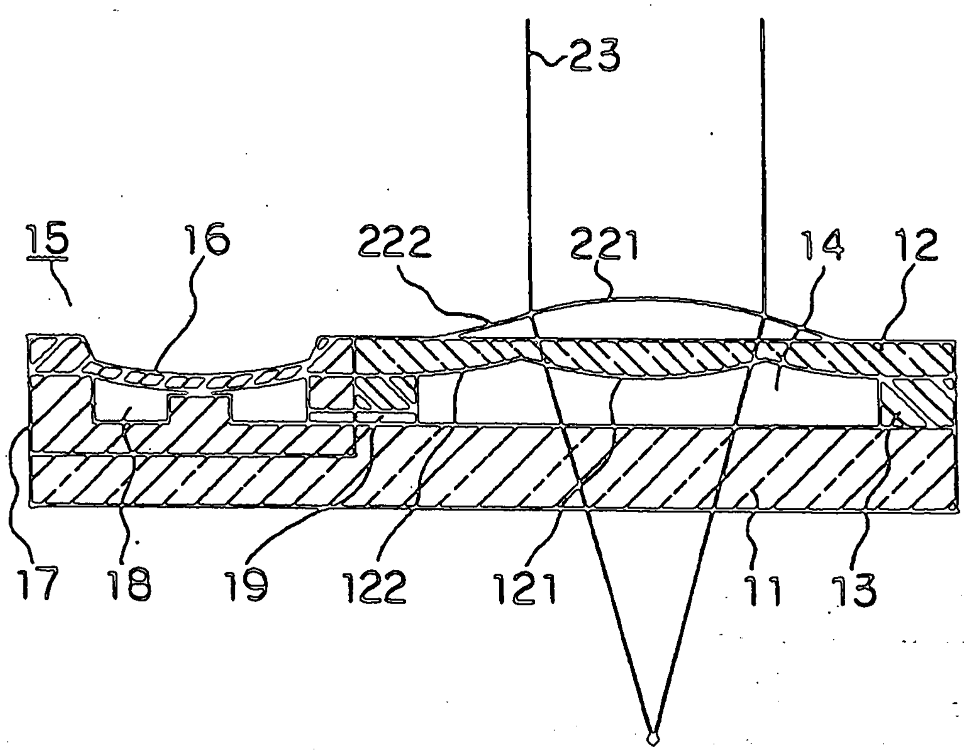


FIG. 1A

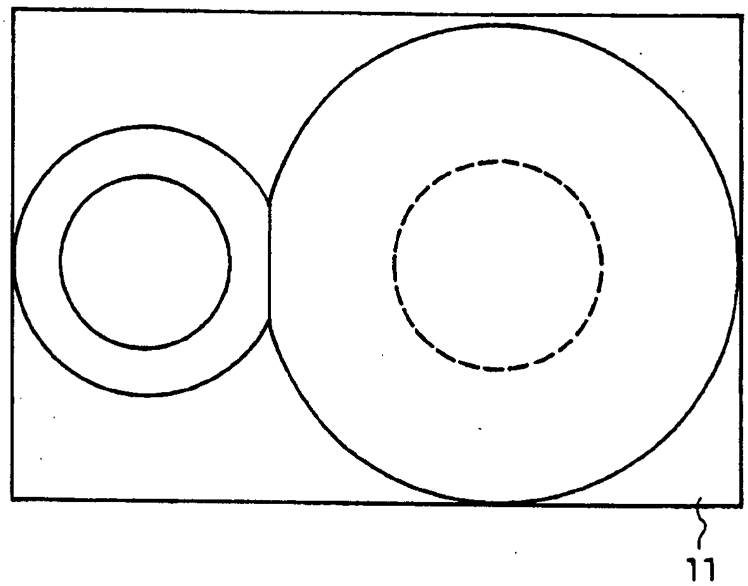


FIG. 1B

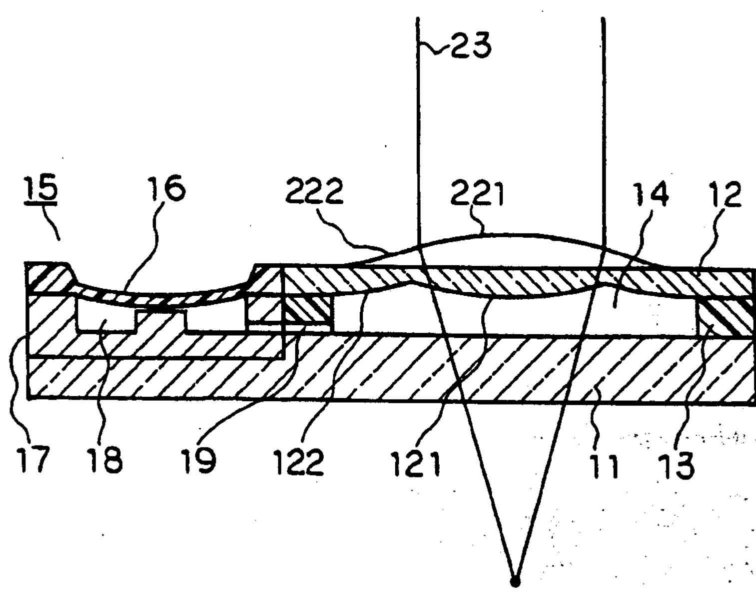


FIG. 2

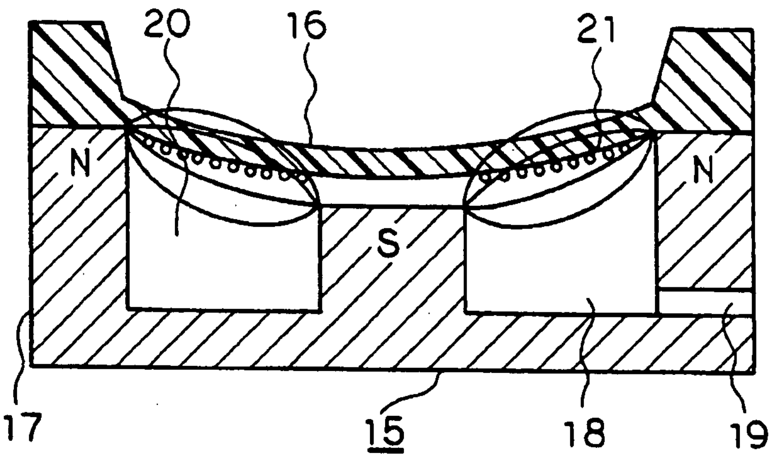

20
16
21
N
N
S
17
15
18
19

FIG. 3

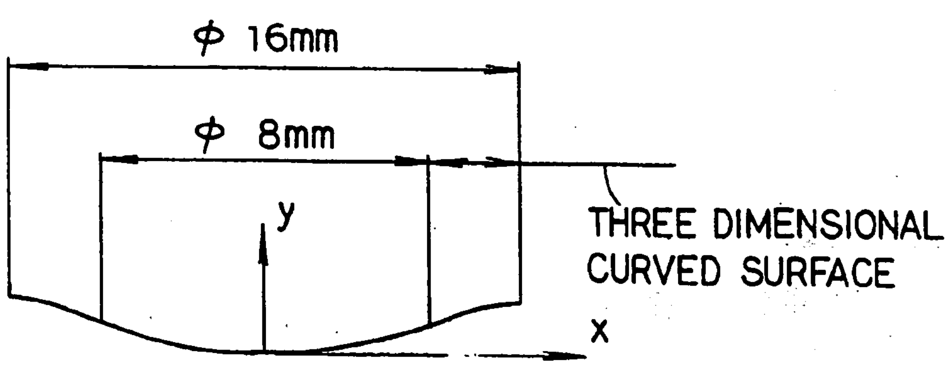

φ 16mm
φ 8mm
y
THREE DIMENSIONAL
CURVED SURFACE
x

FIG. 4

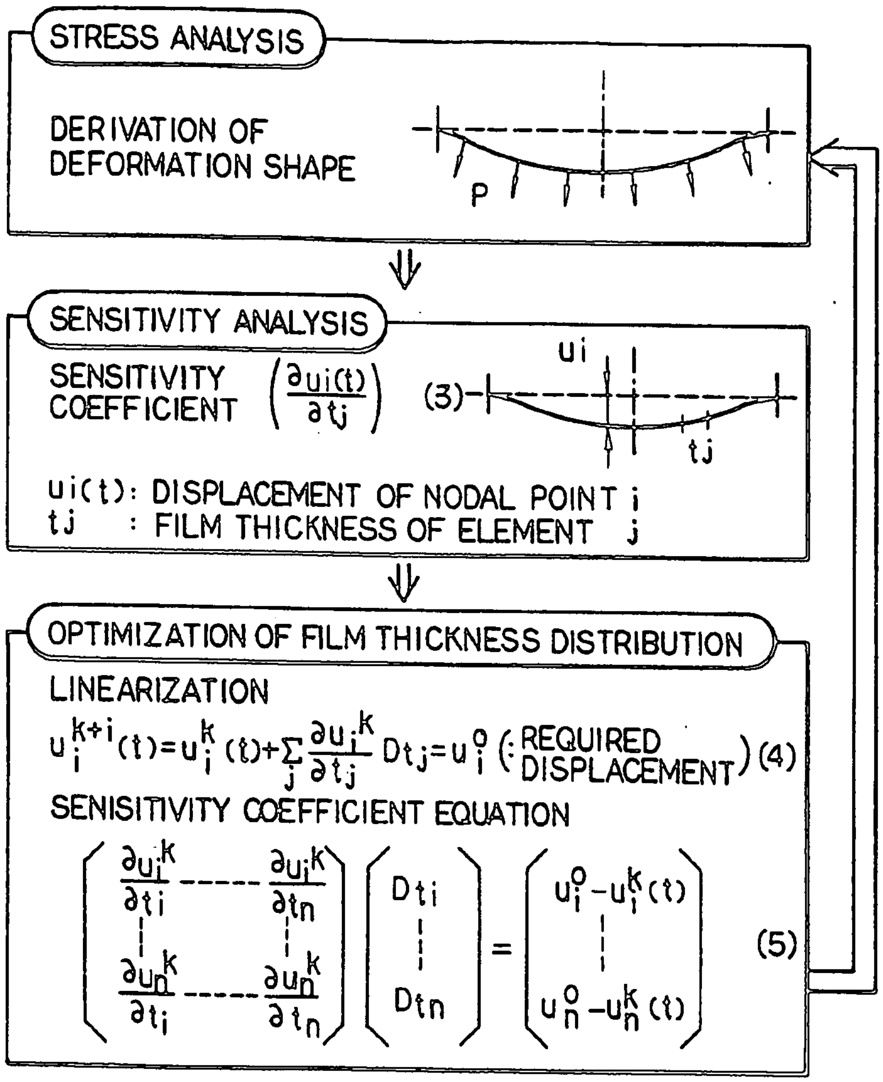

STRESS ANALYSIS
DERIVATION OF DEFORMATION SHAPE
P
SENSITIVITY ANALYSIS
SENSITIVITY COEFFICIENT $\left(\frac{\partial ui(t)}{\partial tj}\right)$ (3)
ui
tj
ui(t): DISPLACEMENT OF NODAL POINT i
tj : FILM THICKNESS OF ELEMENT j
OPTIMIZATION OF FILM THICKNESS DISTRIBUTION
LINEARIZATION
$u_i^{k+i}(t)=u_i^k(t)+\sum_j \frac{\partial u_i^k}{\partial t_j} Dt_j=u_i^o$ (: REQUIRED DISPLACEMENT) (4)
SENISITIVITY COEFFICIENT EQUATION
$\begin{pmatrix} \frac{\partial u_i^k}{\partial t_i} & \cdots & \frac{\partial u_i^k}{\partial t_n} \\ \vdots & & \vdots \\ \frac{\partial u_n^k}{\partial t_i} & \cdots & \frac{\partial u_n^k}{\partial t_n} \end{pmatrix} \begin{pmatrix} Dt_i \\ \vdots \\ Dt_n \end{pmatrix} = \begin{pmatrix} u_i^o-u_i^k(t) \\ \vdots \\ u_n^o-u_n^k(t) \end{pmatrix}$ (5)

FIG. 5

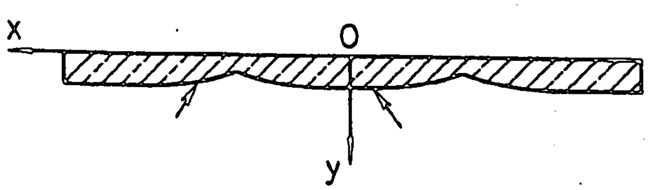

X
O
y

FIG. 6A

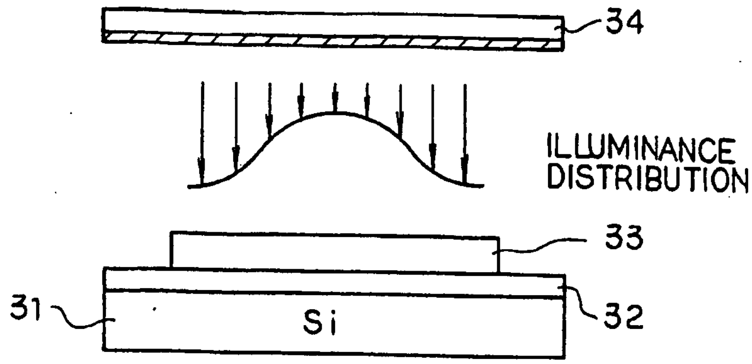


FIG. 6B

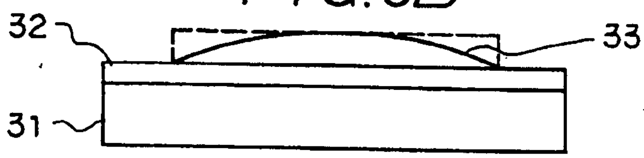


FIG. 6C

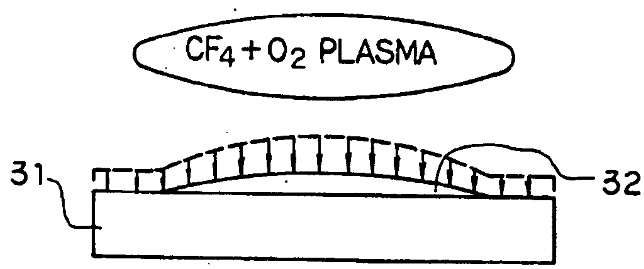
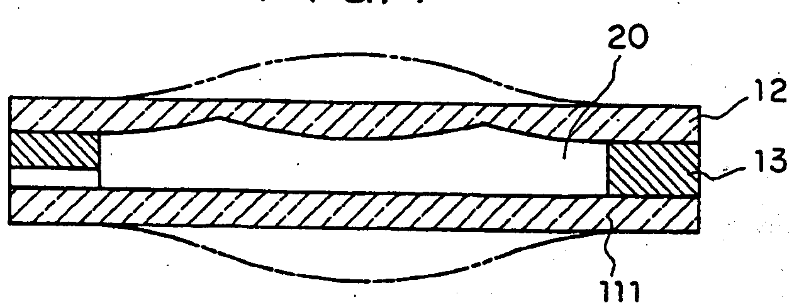


FIG. 7



VARIFOCAL LENS

BACKGROUND OF THE INVENTION

The present invention relates to a varifocal lens which is controllable in focal length and suitable for use in, for example, bar code readers.

Various types of varifocal lenses having a controllable focal length have been proposed in related art. For instance, JP-A-55-36857 (unexamined publication of Japanese patent application) discloses a structure comprising a functional liquid such as silicone oil enclosed in an airtight chamber defined between a pair of transparent elastic films faced to each other with a predetermined spacing provided therebetween. In this varifocal lens, pressure is applied to the operating liquid charged inside the chamber defined between the pair of transparent elastic films to deform the transparent elastic films into a convex shape. In this manner, for example, a convex lens having a bulged center portion can be obtained.

The morphology of such lens as described above changes depending on the rigidity of the transparent elastic films. In a case where the flexural rigidity is predominant in the transparent elastic films, the films undergo deformation to give a fourth order curved plane. In a case where tensile strength is predominant, the transparent elastic films deform to yield a spherical shape.

The varifocal lens must have a quick response from the viewpoint of making it suitable for various applications. Quick response varifocal lenses can be achieved by using a highly rigid material. However, because of the pressure applied to the operating liquid, the use of transparent elastic films made of a rigid material results in the formation of a lens having a fourth order curved surface. The formation of such a lens leads to the generation of aberrations which make it difficult to read, for example, bar codes.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a varifocal lens having a variable focal length which obviates the drawbacks of the conventional varifocal lens.

It is a further object of the present invention to provide a varifocal lens that is controlled by a pressure chamber defined by a pair of transparent films and filled with an operating liquid which applies pressure to the transparent films to elastically deform the films, provided that the shape of the deformed transparent films is optimized in such a manner to minimize the lens aberration.

The varifocal lens according to the present invention comprises a first and a second transparent films at least one of which is made of an elastic material. The first and second transparent films are arranged in parallel with each other with a predetermined spacing therebetween. The operating liquid that is sealed inside the chamber has a refractive index equivalent to that of the first and second transparent films. At least one of the transparent films made of an elastic material is variably deformed by controlling the pressure applied to the transparent film using a pumping means to control said operating liquid. Film thickness distribution can be set in such a manner that the radius of curvature in the center portion may differ from that in the peripheral portion.

In the varifocal lens of the above construction, various types of lenses can be provided by changing the shape of the transparent films, in particular, those made of the elastic material. The shape of the transparent films is controlled by applying variable pressure according to operating liquid placed between the first and the second transparent films. If a highly rigid material is used to form the transparent film made of the elastic material, the deformed film yields a fourth order curved shape which leads to the generation of lens aberration. However, if the transparent film made of an elastic material comprises such a distribution in film thickness as to yield a radius of curvature in the center portion differing from that in the peripheral portion, the film deformed into a fourth order curved shape can be modified to yield a lens having a variable focal length yet which is free of aberrations.

BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings:

FIGS. 1A and 1B are schematic views showing a varifocal lens according to an embodiment of the present invention, FIG. 1A being a plan view and FIG. 1B being a cross-sectional view thereof;

FIG. 2 is a cross sectional view showing the structure of a pump portion for the operating liquid according to the above embodiment of the present invention;

FIG. 3 is a cross sectional view for explaning the shape of a deformed transparent elastic film constituting the lens with reference to FIGS. 1A and 1B;

FIG. 4 is a diagram for explaning the calculation scheme for determining the optimal film thickness distribution of a transparent elastic film;

FIG. 5 is a diagram for explaining the optimal film thickness distribution derived from the calculation scheme with reference to FIG. 4;

FIGS. 6A to 6C are diagrams showing schematically drawn step-sequential cross sectional structures obtained in a process for fabricating a transparent elastic film having a predetermined film thickness distribution; and

FIG. 7 is a cross sectional view of a varifocal lens according to another embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention is described in further detail below in terms of presently preferred embodiments according to the present invention, with reference to the accompanying drawings. It should be understood, however, that the present invention is not to be construed as being limited to the embodiments described hereinafter.

Referring to FIGS. 1A and 1B, a varifocal lens according to an embodiment comprises a glass substrate 11 having upper and lower planar surfaces parallel with each other, and a transparent elastic film 12 provided above a surface of the glass substrate 11 with a predetermined gap therefrom. The transparent elastic film 12 must be a thin film having a film thickness distribution such that it may yield a first curved plane 121 in the central portion and a second curved plane 122 around the peripheral portion of the first curved plane 121.

The outer peripheral portion of the transparent elastic film 12 is joined with the surface of the glass substrate 11 by means of a ring-like spacer 13 made of, for example, silicone. Thus, a pressure chamber 14 surrounded by the spacer 13 is established between the glass substrate 11 and the transparent elastic film 12.

A pump 15 common to the glass substrate 11 is provided adjacent to the pressure chamber 14. Referring to the enlarged view shown in FIG. 2, the pump 15 comprises a thin elastic film 16 made of an insulator. The outer periphery of the elastic film 16 is joined to the outer periphery of a yoke 17 which constitutes a magnetic circuit formed into a cylindrical vessel having a bottom plane. A pressure chamber 18 is formed in this manner inside the yoke 17.

The pressure chamber 18 communicates with the pressure chamber 14 defined by the transparent elastic film 12 via a communicating path 19. The pressure chambers 14 and 18 are filled with an operating liquid 20 such as silicone oil, having the same refractive index as that of the transparent elastic film 12 and the glass substrate 11.

The yoke 17 comprises a cylindrical outer peripheral portion to which the outer periphery of the elastic film 16 is joined, and a center pole provided in such a manner that the front or upper edge thereof may be brought into the vicinity of the elastic film 16. As illustrated in the figure, the cylindrical outer periphery of the yoke 17 functions as N pole, and the center pole functions as S pole. A helical sheet coil 21 is formed on the inner surface of the pressure chamber 18 of the elastic film 16 in such a manner that the center pole may be surrounded thereby.

A DC electric current is supplied selectively to the sheet coil 21. The elastic film 16 undergoes deformation because it is attracted to the center pole inside the yoke 17 due to the Lorentz's force generated by the interaction between the current and the magnetic force of the yoke 17. The volume of the pressure chamber 14 is decreased in this manner. Accordingly, the operating liquid 20 is sent from the pressure chamber 18 to the chamber 14 via the communicating path 19 by the pressure applied to the operating liquid 20. The transparent elastic film 12 is then pushed upward to form curved faces 221 and 222 as shown in FIG. 1B.

The curved faces 221 and 222 then function as a lens. Accordingly, laser light 23 radiated thereonto is focused in the manner shown in FIG. 1B. The focal length depends on the quantity of the operating liquid 20 that is provided by the pump 15. This signifies that the focal length of the lens can be controlled by the magnitude of electric current supplied to the sheet coil 21 of the pump 15.

As the pressure of the operating liquid 20 inside the pressure chamber 14 increases to deform the transparent elastic film 12 to give curved faces 221 and 222, the curved surface 221 in the central portion provides a spherical shape due to the film thickness distribution of the curved surfaces 121 and 122. Thus, the lens aberration of a lens formed in this manner can be improved over that of a conventional lens having no film thickness distribution. This can be seen clearly in Table 1 below.

TABLE 1

Present Embodiment (I)			Prior art (II)	
Pressure [Pa]	Focal length [mm]	spot size [μm]	Focal length [mm]	Spot size [μm]
40	619.8	63.9	22.5	202.4
50	495.9	30.2	577.5	201.2
64	387.3	31.0	451.1	200.9
70	353.9	32.1	412.4	201.4

(I) With film thickness distribution.
(II) A uniform film thickness of 20 μm.

The optimal film thickness distribution for the transparent elastic film 12 is derived as explained below.

Referring to FIG. 3, consideration is given to a certain focus length, for example, 400 mm in this case. The deformed morphology for the transparent elastic film 12 is set to an ideal shape. For instance, the central portion of the transparent elastic film 12 is considered to have a spherical morphology expressed by Equation (1) below, and the peripheral portion thereof is set as a third order curved plane expressed by Equation (2) in such a manner that the boundary conditions may be satisfied in both the spherical plane and the peripheral portion. The pressure of the operating liquid 20 is set to 54 Pa.

Equation for the spherical plane:

$$y=R-(R^2-x^2)^{1/2} \tag{1}$$

where R=200 mm (equivalent to f=400 mm)

Equation for the third order curved plane:

$$y=a_0+a_1x+a_2x^2+a_3x^3 \tag{2}$$

where,

$a_0=-0.80064$

$a_1=0.40032$

$a_2=-0.002505$

$a_3=2.5\times10^{-7}$

Thus, a film thickness distribution is provided as such to the transparent elastic film 12 that the deformed shape as defined above is realized when pressure is applied to the transparent elastic film 12 in the pressure chamber 14 by the operating liquid 20. The calculation process is described below referring to FIG. 4.

The calculation process is performed in three steps. The first step corresponds to stress analysis. The deformation of the transparent elastic film 12 upon application of pressure from the operating liquid 20 is analyzed by means of a finite element method (FEM). The calculation is initiated on a parallel plane transparent elastic film.

The second step comprises sensitivity analysis. This step determines the degree of change in displacement, i.e. the differential coefficient for e.g. a nodal point i of the element j with a change in film thickness of an element. The differential coefficient thus obtained is the sensitivity coefficient. The sensitivity coefficient is expressed by the partial differential shown in Equation (3). The differential coefficient is obtained for each of the combinations of the element j and nodal point i.

The third step comprises the optimization of film thickness distribution. Consider a case in which the film thickness for all of the elements is changed by Δt_j. Then, the deformation u_i^k of a nodal point i can be expressed by Equation (4) shown in FIG. 4 using the sensitivity coefficient obtained in the sensitivity analysis. Thus, optimization is effected in such a manner that u_i^{k+1} may be equal to the required displacement u_i^0 for a nodal point i.

Equation (4) shows the requirement for a nodal point i. The requirements for all the nodal points can be accommodated in a matrix or sensitivity coefficient equation (5). Thus, the displacement of the film thickness by Δt_j can be obtained by solving the matrix (5). However, Equation (4) does not hold in cases where there is a drastic change in film thickness, because the equation is based on the assumption that the film thickness changes in linear relationship with the displacement of the nodal points. In such a case, the transparent elastic film with the calculated film thickness distribution is subjected to stress analysis again to obtain the displaced shape at the given film thickness distribution. The three steps of calculation are repeated until the deformed shape converges.

FIG. 5 shows a transparent elastic film 12 obtained as a result of the above calculation. The result is approximated

by two polynomials. Thus, the central portion of the transparent elastic film 12 is expressed approximately by a fourth order function shown in Equation (6), and the peripheral portion thereof is expressed by a fifth order function shown in Equation (7) below.

Curve A:

$$y=a_0+a_2x^2+a_4x^4 (\mu m) \tag{6}$$

where,

$a_0=1.8472\times10^{-2}$

$a_2=-1.5204\times10^{-4}$

$a_4=-3.6601\times10^{-5}$

Curve B:

$$y=b_0+b_1x^1+b_2x^2+b_3x^3+b_4x^4+b_5x^5 \tag{7}$$

where,

$b_0=0.25648$

$b_1=-0.26049$

$b_2=0.10044$

$b_3=-1.8134\times10^{-2}$

$b_4=1.5751\times10^{-3}$

$b_5=-5.3111\times10^{-5}$

The film thickness distribution thus obtained is for the case in which the transparent elastic film 12 is deformed ideally under a predetermined pressure. Accordingly, the film thickness distribution thus obtained does not guarantee that the deformed shape becomes ideal when the pressure of the operating liquid 20 is changed. The results under various pressures inclusive of the pressure initially set for determining the film thickness distribution for the transparent elastic film 12 above are described below.

The deformed shapes of the transparent elastic film 12 under various pressures can be determined by the aforementioned stress analysis. A parallel incident beam 8 mm in diameter is radiated onto the lens to obtain the spot diameters listed in Table 1.

Table 1 also shows, as a comparative example, a case in which parallel transparent elastic films are used. The case having a film thickness distribution yields a spot diameter of 30 μm for a focal length in the range of from about 350 to 600 mm. This is in good contrast with a conventional case having a uniform film thickness which yields a spot diameter of about 200 μm for a comparative focal length. It can be seen that the aberration for a lens having a uniform film thickness can be reduced to about one-seventh by introducing film thickness distribution.

The film thickness distribution can be obtained in the manner described above. A method for providing film thickness distribution in a transparent elastic film 12 is described below. Referring to FIG. 6A, a glass (Pyrex glass) 32 is anodically welded to the surface of a silicon wafer 31 that is provided as the substrate. The silicon wafer 31 and the glass 32 are each several hundreds of micrometers in thickness. The glass 32 is cut and polished thereafter to reduce the thickness thereof to a desired value of about several tens of micrometers. The cutting and polishing of the glass must be conducted with care so that the parallel planes may be maintained. The surface of the resulting glass 32 is coated with a positive photoresist 33 at a thickness corresponding to the irregularities of the film thickness distribution, and the surface of the positive photoresist 33 is then exposed to light via a photomask 34 according to the film thickness distribution.

The surface of the positive photoresist 33 can be exposed by, for example, two-dimensional scanning a laser light while changing the intensity thereof, or by imparting light exposure distribution using a dither for the photomask 34.

The resulting structure subjected to light exposure is developed thereafter. Referring to FIG. 6B, it can be seen that a curve corresponding to the light exposure distribution is formed on the photoresist 33. Dry etching for simultaneously etching both the photoresist 33 and the glass 32 is effected after once a curve corresponding to the film thickness distribution is formed on the photoresist 33. Oxygen and CF_4 are used as the etchants for the photoresist 33 and the glass 32, respectively. Accordingly, the two etchants are mixed at a proper mixing ratio and are applied at an appropriate pressure for dry etching to transfer the curve corresponding to the film thickness distribution formed on the photoresist 33 onto the glass 32. The silicon wafer 31 is then removed from the back by wet etching using KOH. Thus, a transparent elastic film having the predetermined film thickness distribution can be formed from glass.

In the embodiment above, the explanation has been made that the glass substrate 11 having a parallel plane faced to the transparent elastic film 12 which deforms by the pressure of the operating liquid does not undergo deformation. However, the substrate portion may be a thin sheet which deforms by the pressure of the operating liquid 20.

Another embodiment based on the concept of a glass substrate which undergoes deformation is shown in FIG. 7. The glass substrate faced to the transparent elastic film 12 having a film thickness distribution is made of an elastic thin film 111 which is provided thin enough to undergo deformation. The elastic thin film has parallel planes and has no distribution in film thickness.

The film thickness distribution of a transparent elastic film 12 in the present embodiment can be determined in the following manner. The elastic thin film 111 provided as the substrate in the present embodiment undergoes morphological change upon application of a pressure by the operating liquid 20. However, it deforms not into a spherical shape and suffers lens aberration. Accordingly, an ideal deformed shape is set for the transparent elastic film 12 having the film thickness distribution as such to cancel out the aberration. Thus, the calculation scheme explained with reference to FIG. 4 can be applied according to the ideal deformed shape.

As described in the foregoing, the varifocal lens according to the present invention comprises a pressure chamber defined by a pair of transparent films and charged therein an operating liquid, so that the transparent film may be elastically deformed by the pressure of the operating liquid and thereby control the focus length of the lens. The varifocal lens according to the present invention above is characterized in that the deformed shape of the transparent film is optimized in such a manner that the lens aberration may be minimized. Thus, the present invention provides an aberration-free varifocal lens whose focal length is variably controlled by the pressure of the operating liquid. Accordingly, the varifocal lens according to the present invention is widely applicable to various optical equipments such as bar code readers.

While the invention has been described in detail and with reference to specific embodiments thereof, it will be apparent to one skilled in the art that various changes and modifications can be made therein without departing from the spirit and scope thereof.

What is claimed is:

1. A varifocal lens comprising:

a first transparent film and a second transparent film, at least one of which is made of an elastic material, said

films being constructed and arranged so as to have peripheral portions thereof sealed to one another and central portions thereof spaced from one another so as to define an inner space therebetween;

an operating liquid disposed Within said inner space and having a refractive index equivalent to a common refractive index of said first and said second transparent films; and

a deformation controlling structure constructed and arranged to control the pressure applied to said operating liquid so as to provide an image-forming optical system by deforming said at least one of said transparent films, and

wherein said at least one of said transparent films has a thickness distribution such that the central portion thereof is circular and has a surface defining a spherical plane, such that said peripheral portion thereof has a surface defining a third order curved plane with a radius of curvature differing from that of the central portion, and such that said circular central portion thereof has its thickness increasing as it extends radially inwardly.

2. A varifocal lens as claimed in claim 1, wherein, said deformation controlling structure comprises:

a casing having an elastic film formed thereon and being connected with said inner space and charged with said operating liquid; and

a pressure-applying means which applies pressure to said operating liquid inside said casing by displacing said elastic film formed on the casing.

3. A varifocal lens as claimed in claim 2, wherein said pressure-applying means has a structure such that said elastic film is displaced by electric current supplied to a coil provided on said elastic film, and the lines of magnetic force generated by a magnet provided inside said casing.

4. A varifocal lens comprising:

a first transparent film and a second transparent film, at least one of which is made of an elastic material, said first transparent film and said second transparent film having peripheral portions sealed to one another and central portions spaced from one another so as to define a pressure chamber therebetween;

an operating liquid disposed within said pressure chamber and having a refractive index equivalent to a common refractive index of said first and second transparent films; and

a deformation controlling structure constructed and arranged to control a pressure applied to said operating liquid introduced into said pressure chamber, thereby controlling a variable pressure applied to said at least one of said transparent films,

wherein said at least one of said transparent films has a thickness distribution such that the central portion thereof is circular and has a surface defining a spherical plane, such that said peripheral portion thereof has a surface defining a third order curved plane with a radius of curvature differing from that of the central portion, and such that said circular central portion thereof has its thickness increasing as it extends radially inwardly.

5. A varifocal lens as claimed in claim 4, wherein said film thickness distribution of said at least one of transparent films is provided as such that a spherical plane may be formed in the central portion and a third order curved plane is formed in the peripheral portion thereof.

6. A varifocal unit comprising:

a first member;

an elastic second member defining a chamber with said first member, said second member comprising a circular central portion and a peripheral portion surrounding said central portion, said central portion having a surface lying in a convex plane and said peripheral portion having a surface lying in another plane, wherein a boundary between said first and second members defines a minimum thickness of said varifocal unit; and

a pressure controlling structure constructed and arranged to control a pressure in said chamber;

said central portion having a thickness which increases as it extends in a radially inward direction from said boundary; and

said another plane of said peripheral portion defining a third order curved plane different from said convex plane.

7. A varifocal unit according to claim 6, wherein:

said first and second members are made of transparent material; and

both said surface of said central portion lying in said convex plane and said surface of said peripheral portion lying in said another plane of said second member face said first member.

8. A varifocal unit according to claim 6, wherein:

said convex plane of said central portion defines a portion of a sphere.

9. A varifocal unit according to claim 6, wherein:

said convex plane of said central portion defines a non-spherical curved plane.

10. A varifocal unit according to claim 7, wherein:

said second member has a substantially flat surface opposite said surfaces facing said first member.

11. A varifocal unit according to claim 6, wherein:

said pressure controlling structure includes a pump positioned outside and communicating with said chamber for controlling fluid flow to and from said chamber.

12. A varifocal unit comprising:

a first member;

an elastic second member defining a chamber with said first member, said second member having a circular central portion and a peripheral portion surrounding said central portion, said central portion having a surface lying in a first curved plane and said peripheral portion having a surface lying in a second curved plane different from said first curved plane; and

a pressure controlling structure constructed and arranged to control a pressure in said chamber; wherein

said first and second members are made of transparent material;

a boundary defines the interface between said central and peripheral portions of said second member; and

said central and peripheral portions of said second member have thicknesses which increase as they extend outwardly away from said boundary therebetween.

13. A varifocal unit according to claim 3, wherein:

said surfaces of said second member lying in said first and second curved planes face said first member; and

an outer surface of said second member opposite said surfaces facing said first member lies in a flat plane.

14. A varifocal unit according to claim 12, wherein:

said peripheral portion of said second member is coupled to said first member with a boundary between said central and peripheral portions being located within said chamber.

* * * * *

US006369954B1

(12) United States Patent
Berge et al.

(10) **Patent No.: US 6,369,954 B1**
(45) **Date of Patent: Apr. 9, 2002**

(54) **LENS WITH VARIABLE FOCUS**

(75) Inventors: **Bruno Berge**, Lyons; **Jerome Peseux**, la Grandemotte, both of (FR)

(73) Assignee: **Universite Joseph Fourier (FR)**

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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(86) PCT No.: **PCT/FR98/02143**

§ 371 Date: **Jul. 25, 2000**

§ 102(e) Date: **Jul. 25, 2000**

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PCT Pub. Date: **Apr. 15, 1999**

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(51) **Int. Cl.**[7] **G02B 1/06**; G02B 26/00; G02F 1/13

(52) **U.S. Cl.** **359/666**; 359/291; 359/665; 349/200

(58) **Field of Search** 359/665, 666, 359/290, 291; 349/200, 57

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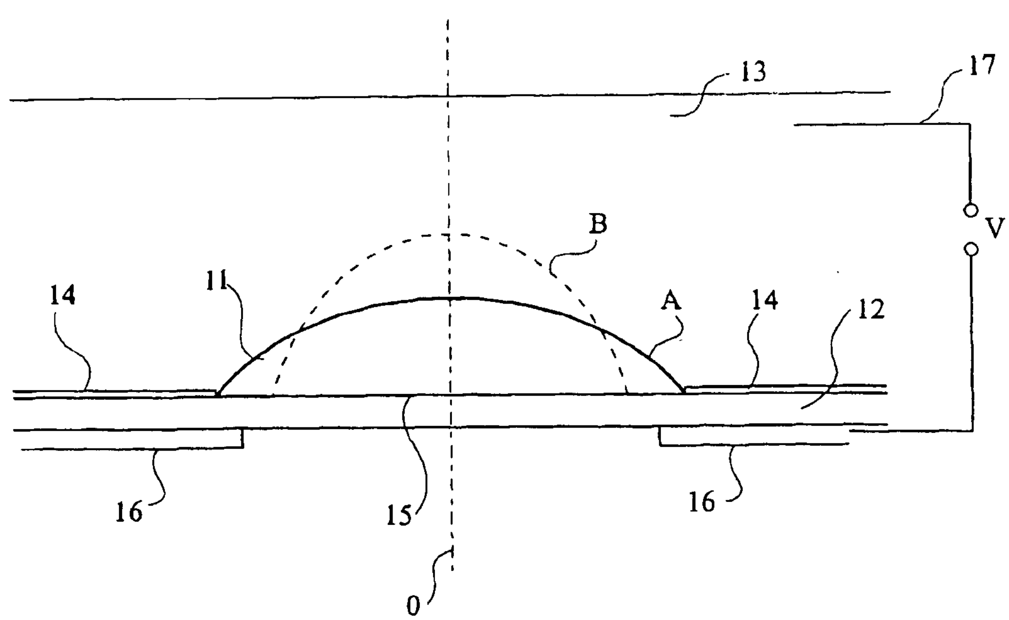
Primary Examiner—Georgia Epps
Assistant Examiner—David N. Spector
(74) *Attorney, Agent, or Firm*—Arthur L. Plevy; Duane Morris

(57) **ABSTRACT**

A variable focus lens comprising a chamber (**12**) filled with a first liquid (**13**), a drop of a second liquid (**11**) being disposed at rest on a region of a first surface of an insulating wall of the chamber, the first and second liquids being non miscible, of different optical indexes and of substantially same density. The first liquid is conductive and the second liquid is insulating. The lens further comprises means for applying a voltage between the conductor liquid and an electrode (**16**) placed on the second surface of said wall; and centering means for maintaining the centering of the edge of the drop while the voltage is applied and for controlling the shape thereof.

10 Claims, 3 Drawing Sheets



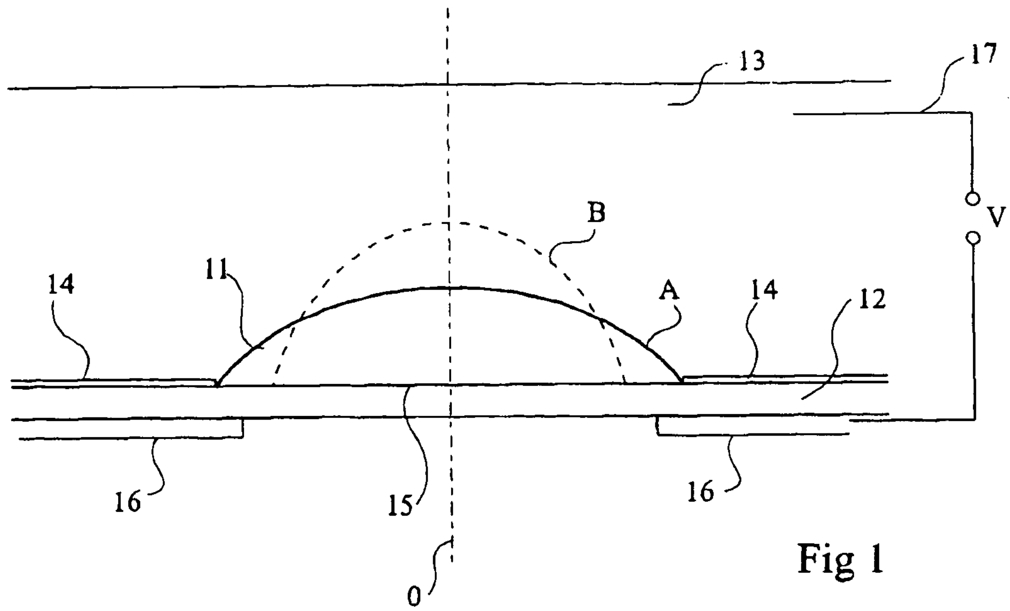


Fig 1

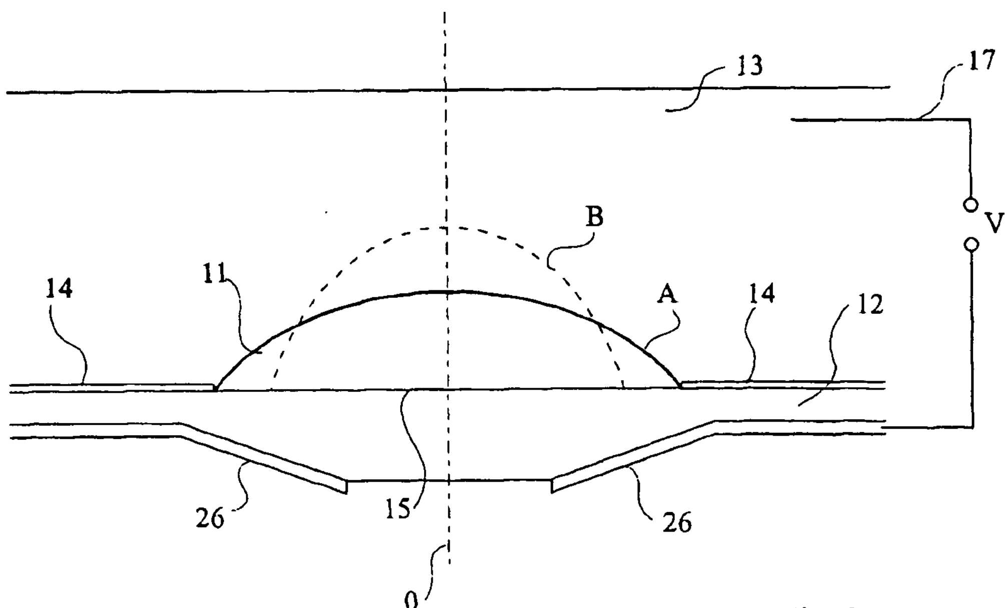


Fig 2

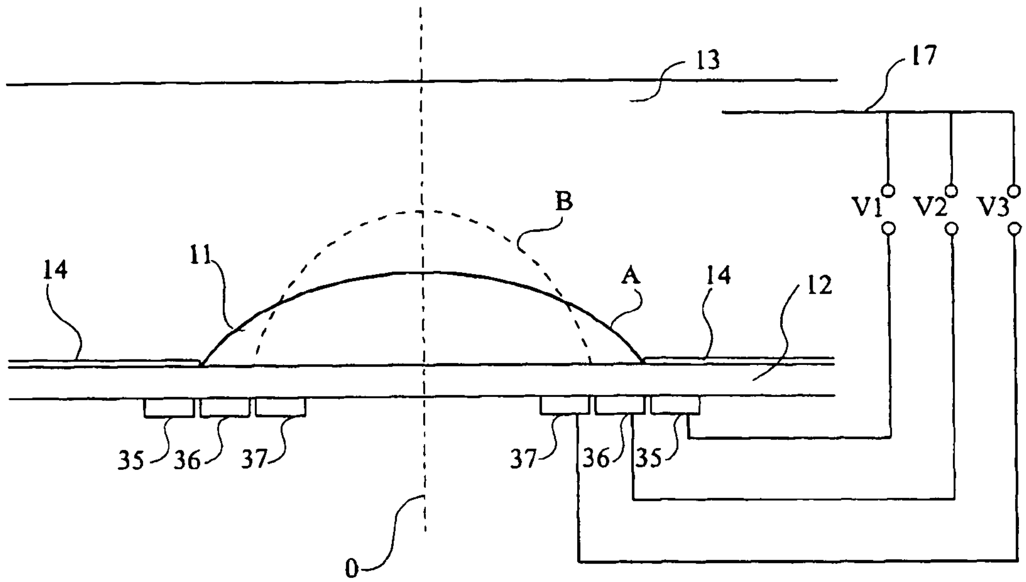

13
17
V1
V2
V3
B
11
14
A
14
12
35
36
37
37
36
35
0

Fig 3

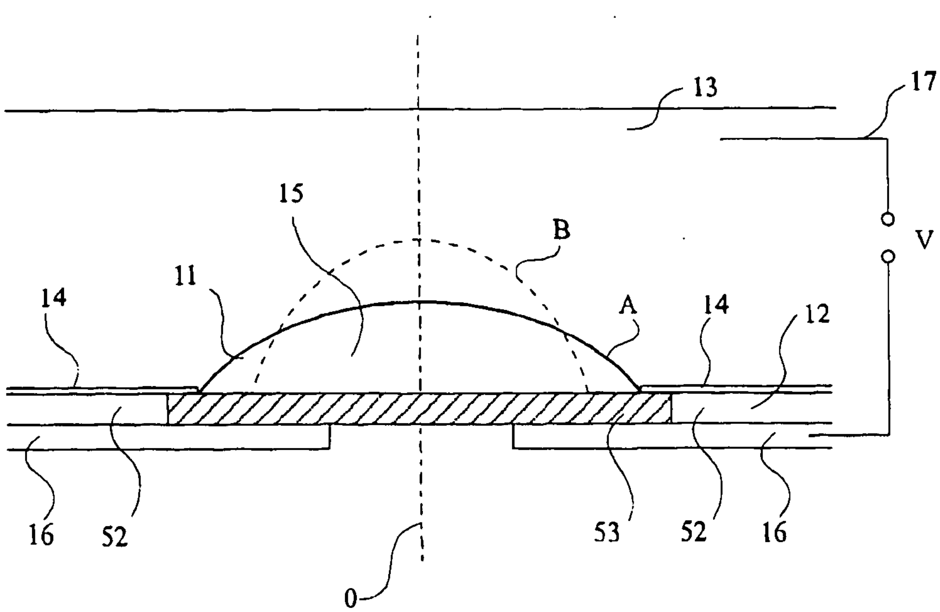

13
17
V
15
B
11
14
A
14
12
16
52
53
52
16
0

Fig 4

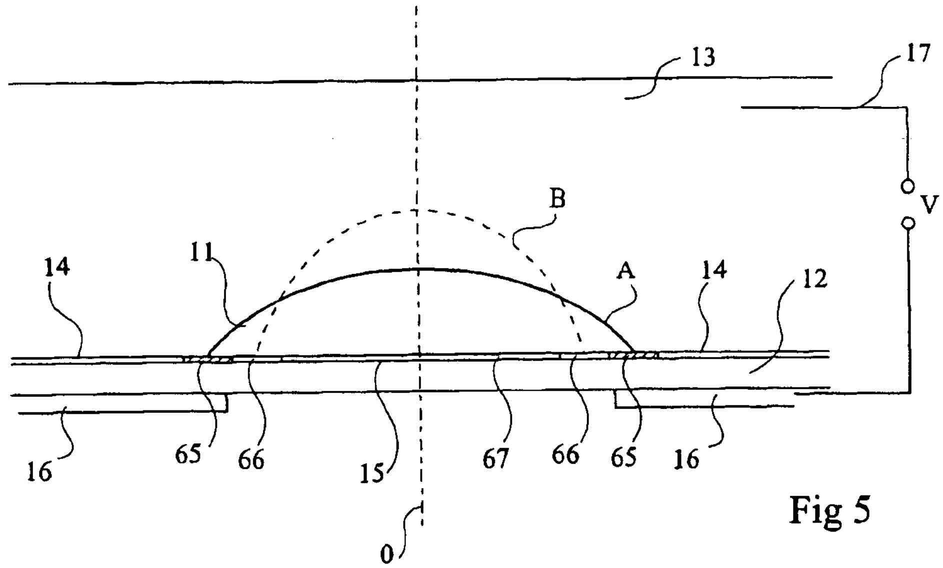

13
17
B
V
14
11
A
14
12
16
65
66
15
67
66
65
16
0

Fig 5

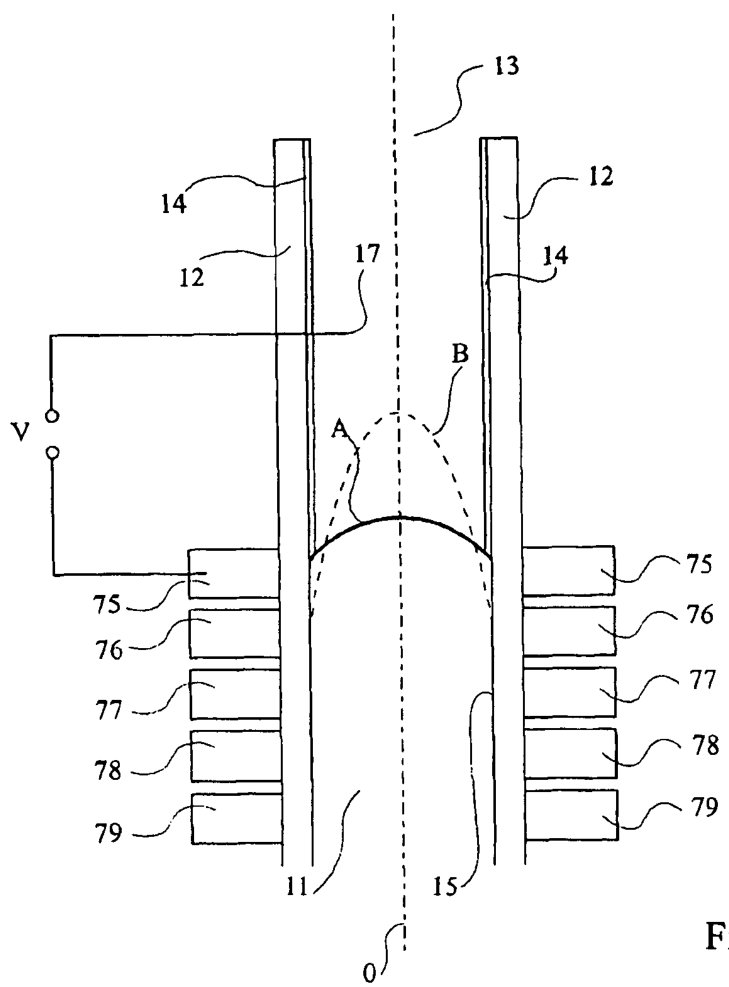

13
12
14
12
17
14
B
V
A
75
75
76
76
77
77
78
78
79
79
11
15
0

Fig 6

LENS WITH VARIABLE FOCUS

BACKGROUND OF THE INVENTION

(1) Field of the Invention

The present invention relates to the field of variable focal lenses, and more specifically to liquid lenses having a variable electrically controlled focus.

(2) Description of Related Art

An article of B. Berge entitled "Electrocapillarité et mouillage de films isolants par l'eau" published in 1993 in C.R. Acad. Sci. Paris, t. 317, serial II, pages 157 to 163, discloses a device comprising a drop of conductor liquid placed on a dielectric film covering a flat electrode. A voltage may be applied between the liquid conductor drop and the electrode. This article describes a theoretical study of the wetting variation of a dielectric material with respect to a conductor liquid and shows that the wetting increases substantially in presence of an electric field caused by the voltage existing between the conductor liquid and the electrode. This phenomenon is called electrowetting by the author.

U.S. Pat. No. 5,659,330 discloses a display device using the electrowetting phenomenon to vary the shape of a drop of opaque conductor liquid placed on a dielectric. This document does not suggest the use as an optic lens.

An article of Vallet, Berge and Vovelle, "Electrowetting of water and aqueous solutions on poly(ethylene terephthalate) insulating films", published in Polymer, Vol. 37, N° 12, pages 2465 to 2470, 1996, discloses a deformation of a liquid conductor drop to which a voltage is applied. It is indicated that, when the applied voltage becomes too high, the surface of the drop becomes unstable, and microdroplets may be ejected at the periphery of the drop.

BRIEF SUMMARY OF THE INVENTION

This makes prior art systems inadequate for forming variable lenses. Moreover, these systems need a transparent biasing electrode and a connection for the electrode, which makes the system difficult to manufacture or inefficient.

An object of the present invention is to provide a lens whose focus may vary continuously as a function of an electric control, by using the phenomenon of electrowetting.

Another object of the present invention is to provide a lens which is simple to manufacture.

Another object of the present invention is to provide a lens which is simple to use.

For achieving these objects, the present invention provides a variable focus lens comprising a chamber filled with a first liquid, a drop of a second liquid being disposed at rest on a region of a first surface of an insulating wall of the chamber, the first and second liquids being non miscible, of different optical indexes and of substantially same density. The first liquid is conductive and the second liquid is insulating. The lens further comprises means for applying a voltage between the conductor liquid and an electrode placed on the second surface of said wall; and centering means for maintaining the centering of the edge of the drop while the voltage is applied and for controlling the shape thereof.

According to an embodiment of the invention, the centering means allows a continuous maintaining of the centering of the drop and a continuous control of the shape of the edge of the drop while a varying voltage is applied by said means for applying a voltage.

According to an embodiment of the invention, the first surface is substantially flat, the contact region is circular and centered about an axis which is perpendicular to the first surface.

According to an embodiment of the invention, the centering means corresponds to a progressive thickening of the second surface of the wall of the chamber towards said axis, said electrode being applied against said second surface.

According to an embodiment of the invention, the centering means corresponds to a radial decrease of the wetting with respect to the first liquid, towards the center of said contact region with the second liquid.

According to an embodiment of the invention, the centering means corresponds to a radial gradient of the dielectric constant of said wall of the chamber at the level of said contact region with the second liquid.

According to an embodiment of the invention, the first surface is substantially flat, the contact region **15** is circular and centered about an axis perpendicular to the first surface, and the centering means comprises an electrode formed of one or several circular concentric strips insulated from each other, centered about said axis, the circular strips being supplied by distinct voltage sources of values decreasing towards said axis.

According to an embodiment of the invention, the chamber is cylindrical, the first surface is the internal surface of the chamber, the contact region with the second liquid corresponds to a cylindrical section of the chamber, the centering means is comprised of one or several cylindrical electrodes of same diameter, insulated from each other, placed side by side against the external surface of the chamber at the level of the border of said contact region, the electrodes being supplied by different voltages of values decreasing towards the center of said contact region.

According to an embodiment of the invention, the first surface is substantially flat, the contact region is rectangular and symmetric with respect to an axis perpendicular to the first surface and the centering means is comprised of an electrode formed of one or several rectangular concentric strips insulated from each other, symmetric with respect to said axis, the rectangular strips being supplied by distinct voltage sources of decreasing values towards said axis.

According to an embodiment of the invention, said wall is comprised of two non parallel planes and in which said region bridges said two planes.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The foregoing and other objects, features, aspects and advantages of the invention will become apparent from the following detailed description of embodiments, given by way of illustration and not of limitation with reference to the accompanying drawings:

FIG. **1** shows a first embodiment of a variable focus lens according to the present invention;

FIG. **2** shows a second embodiment of a variable focus lens according to the present invention;

FIG. **3** shows a third embodiment of a variable focus lens according to the present invention;

FIG. **4** shows a fourth embodiment of a variable focus lens according to the present invention;

FIG. **5** shows a fifth embodiment of a variable focus lens according to the present invention; and

FIG. **6** shows another embodiment of a variable focus lens according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 shows a simplified cross-section view of a variable focus liquid lens according to a first embodiment of the present invention. A drop of an insulating liquid 11 is located on the internal surface of a wall of a dielectric chamber 12 filled with a conductor liquid 13. The insulating liquid 11 and the conductor liquid 13 are both transparent, not miscible, have different optical indexes and have substantially the same density. The dielectric 12 naturally has a low wetting with respect to the conductor liquid 13. A surface treatment 14 insuring a high wetting of the wall of the dielectric chamber with respect to the conductor liquid 13 surrounds the contact region 15 between the insulating liquid drop 11 and the wall of chamber 12. The surface treatment 14 maintains the positioning of drop 11, preventing the insulating liquid from spreading beyond the desired contact surface. When the system is at rest, the insulating liquid drop 11 naturally takes the shape designated by reference A. "O" designates the axis which is perpendicular to the contact region 15 and passing through the center of contact region 15. At rest, the insulating liquid drop 11 is centered about axis O which constitutes the optical axis of the device. The elements of the device which are adjacent to axis O are transparent. An electrode 16, letting through light in the vicinity of axis O, is placed on the external surface of the wall of dielectric chamber 12, on which is situated the insulating liquid drop 11. An electrode 17 contacts the conductor liquid 13. Electrode 17 may be immersed in liquid 13, or be a conductor deposition achieved on an internal wall of chamber 12.

When a voltage V is established between electrodes 16 and 17, an electrical field is created which, according to the above mentioned electrowetting principle, will increase the wetting of region 15 with respect to conductor liquid 13. As a consequence, conductor liquid 13 moves and deforms the insulating liquid drop 11. A variation of the focus of the lens is thus obtained.

However, the center of the drop is likely to move with respect to axis O during the deformation. Moreover, the outline of the contact surface is likely to lose its circular character during the deformation of the drop. An aspect of the present invention is to maintain the circularity of the drop and its concentricity with respect to axis O while its shape changes by generating an electric field which decreases radially towards the center of region 15.

For avoiding this, according to an aspect of the present invention, a centering means for drop 11 is additionally provided. Examples of such centering means appear in the second to sixth embodiments of the invention described hereinafter.

FIG. 2 shows a simplified cross-section view of a variable focus liquid lens according to a second embodiment of the present invention. Elements such as drop 11, axis O, chamber 12, conductor liquid 13, surface treatment 14, contact region 15 and electrode 17 are the same as those of the embodiment illustrated in FIG. 1. The positions A and B also correspond to the rest position of drop 11 and to the limit position of drop 11, respectively. In this second embodiment, the centering means comprises the generation of an electrical field which decreases radially towards the center of region 15. For this purpose, an electrode 26 is provided which has a surface which progressively departs from the surface of region 15 while approaching axis O. Such an electrode 26 may, for example, be obtained by depositing a metallic film on the lateral walls of a taper centered about axis O, achieved on the external surface of the wall of chamber 12 on which is placed drop 11. An alternative embodiment may consist in depositing a metallic film on the surface of a transparent dielectric resin drop centered about axis O, attached to the external surface of the wall of chamber 12 on which drop 11 is placed. The top of the resin drop is planed in the vicinity of axis O to let the light through.

One may increase voltage V from O volt to a maximum voltage which depends on the used materials. When the maximum voltage is reached, the insulating liquid drop 11 reaches a limit position (designated by reference B). When voltage V varies continuously between O volt and its maximum value, the insulating liquid drop 11 continuously deforms from position A to position B. It will be noted that, drop 11 being of an insulating liquid, no microdroplets are produced at its periphery when the voltage is high, in contrast to what would happen if the drop was of a conductor liquid (see the above mentioned article of Vallet, Berge and Vovelle).

FIG. 3 shows a simplified cross-section view of a variable focus liquid lens according to a third embodiment of the present invention. Elements such as drop 11, axis O, chamber 12, conductor liquid 13, surface treatment 14, contact region 15 and electrode 17 are the same as those of the embodiment described in FIG. 1. The positions A and B also correspond to the rest position of drop 11 and to the limit position of drop 11, respectively.

In this third embodiment, on the external surface of the wall of chamber 12 is placed a group of three circular concentric electrodes, 35, 36 and 37, insulated from each other, and having O as axis. A voltage may be applied between each of electrodes 35, 36 and 37 and electrode 17; exemplary voltages V1, V2 and V3 are shown, each of which may vary. The voltages are chosen at any time with decreasing values towards axis O so that the electric field generated by applying the voltages to electrodes 35, 36 and 37 decreases radially towards the center of region 15. When voltages Vl, V2 and V3 continuously vary between 0 volt and their maximum value, the insulating liquid drop 11 deforms continuously between its rest position A and its limit position B.

According to an alternative of this third embodiment, each electrode 35, 36 and 37 may be connected by a switch, either to a same voltage source V, either to ground. For a constant voltage V, the shape of drop 11 is then varied by varying the number of electrodes to which a voltage is applied. In this case, the focus variation is discrete and not continuous. Only certain predetermined focuses can thus be obtained for the lens comprised of drop 11, but the benefit is then that the voltage control is relatively simple to implement.

FIG. 4 shows a simplified cross-section view of a variable focus liquid lens according to a fourth embodiment of the present invention. Elements such as drop 11, axis O, conductor liquid 13, surface treatment 14, contact region 15 and electrodes 16 and 17 are the same as those of the embodiment described in FIG. 1. The positions A and B also correspond to the rest position of drop 11 and to the limit position of drop 11, respectively.

In this fourth embodiment, the wall of the dielectric chamber 52 on which the insulating liquid drop 11 is placed, comprises a circular dielectric region 53, letting through the light about axis O. Region 53 has a low wetting with respect to conductor liquid 13 in the absence of a surface treatment 14. Region 53 has been treated in such a way that its

dielectric constant varies radially and continuously towards axis O, and that the electric field generated by voltage V has a gradient which decreases radially towards axis O on the contact region **15**. When voltage V is varied continuously between 0 volt and its maximum value, the insulating liquid drop **11** continuously deforms between its rest position A and its limit position B.

FIG. **5** shows a simplified cross-section view of a variable focus liquid lens according to a fifth embodiment of the present invention. Elements such as drop **11**, axis O, dielectric chamber **12**, conductor liquid **13**, contact region **15** and electrodes **16** and **17** are the same as those of the embodiment described in FIG. 1. The positions A and B also correspond to the rest position of drop **11** and to the limit position of drop **11**, respectively.

In this fifth embodiment, the surface of the wall of dielectric chamber **12** on which the insulating liquid drop **11** is placed has been treated at different regions **14**, **65**, **66** and **67** such that the wetting of regions **14**, **65**, **66** and **67** with respect to conductor liquid **13** decreases radially towards axis O. A voltage V may be applied between electrode **16** and electrode **17**. The electric field generated by voltage V increases the wetting of regions **14**, **65**, **66** and **67** but maintains the initial wetting gradient. When voltage V varies between 0 volt and its maximum value, the shape of the insulating liquid drop **11** continuously varies between its rest position A and its limit position B.

FIG. **6** shows a simplified cross-section view of another embodiment of the present invention in which an insulating liquid **11** occupies the bottom portion of a cylindrical dielectric chamber and is covered by a conductor liquid **13**. The chamber is designated by reference **12**. The materials composing elements **11**, **12** and **13** are the same as those of the previous embodiments.

A surface treatment **14** insuring a high wetting of the internal wall of chamber **12** with respect to the conductor liquid **13** is achieved above the contact region **15** between liquid **11** and the internal surface of chamber **12**. The surface treatment **14** allows the position of liquid **11** to be maintained for avoiding this liquid from spreading beyond the contact surface. For simplifying the description only the top portion of liquid **11** will be considered and it will be called, like in the previous embodiment, "drop **11**". When the system is at rest, the insulating liquid drop **11** naturally takes the shape designated by reference A. Axis O is the axis of chamber **12**. At rest, the insulating liquid drop **11** is centered about axis O which constitutes the optical axis of the device. Several electrodes **75**, **76**, **77**, **78**, **79** are placed about the external wall of dielectric chamber **12** in the vicinity of contact region **15**. The electrodes **75**, **76**, **77**, **78**, **79** are insulated from each other and a voltage V is established between electrode **75** and an electrode **17** contacting the conductor liquid **13**. The electrodes **76**, **77**, **78**, **79** are biased through capacitive influence when voltage V is established. At wall **12**, the electric field generated by voltage v decreases according to a longitudinal gradient from electrode **75** towards electrode **79**. When voltage V increases, conductor liquid **13** moves and deforms the insulating liquid drop **11**. A variation of the focus of the lens is thus obtained. The above-mentioned electric field gradient insures that the drop permanently has a radial symmetry with respect to axis O. When voltage V varies between 0 volt and its maximum value, the insulating liquid drop **11** varies continuously between its rest position A and its limit position B.

Those skilled in the art will be able to combine the features appearing in the various embodiments of the invention described above.

Moreover, the present invention may be subject to various alternatives which will appear to those skilled in the art.

The surface of the dielectric chamber **12** of FIG. **1** may be concave or convex, in order to obtain a particular diopter value of the device at rest.

The contact region between the insulating liquid drop and the dielectric chamber may be treated for having a high wetting with respect to the insulating liquid, in order to simplify the positioning of the insulating liquid drop.

In the case of a dielectric chamber naturally having a high wetting with respect to the conductor liquid, the contact region may be achieved by a surface treatment adapted to providing it with a low wetting with respect to the conductor liquid.

The surface treatment **14** may consist of depositing or sticking a film of a material having a high wetting with respect to conductor liquid **13**.

Electrode **16** of FIG. **1** may be replaced with a conductor liquid in contact with the external surface of chamber **12**, voltage V then being established between this conductor liquid and liquid **13**.

It will be possible to realize a device including an array formed of groups of three, separately controlled, variable focus lenses, colored in red, green, and blue, operating, for example, in a binary mode, stopping or allowing through light originating from a unique source of white light, thus forming a luminous color screen which may be of big size and of moderate cost.

It will be possible to realize a device in which the above mentioned centering means are no longer used for maintaining drop **11** circular throughout its deformation, but in contrast for making the drop go from a rest position determined, for example, by the shape of the surface treatment **14**, to an operating shape, determined, for example, by the outline of electrode **16**. It is thus possible to create a variable focus cylindrical lens by using a surface treatment **14** of rectangular shape and centering electrodes **16** of rectangular outline.

It will be possible to apply the present invention to a device bridging more than one wall of chamber **12**, drop **11** being placed, for example, in an angle or in a corner of chamber **12**. According to this alternative, an electrode would of course be placed on the back surface of each wall in contact with drop **11**, at the level of the contact region. Such an alternative would enable a variable deflection prism to be achieved.

As an example of conductor liquid **13**, one may use water loaded with salts (mineral or other) or any other liquid, organic or not, which is conductive or made conductive by addition of ionic components. As an insulating liquid **11**, one may use oil, an alcane or a blend of alcanes, eventually halogenated, or any other insulating liquid which is not miscible with conductor liquid **13**. Chamber **12** may be comprised of a glass plate, treated with silane or covered with a thin coating of fluorinated polymer or of a sandwich of fluorinated polymer, epoxy resin, polyethylene.

Voltage V will preferably be alternating in order to avoid the accumulation of electric charges throughout material **12** from the surface on which drop **11** is placed.

In the exemplary embodiment of FIG. **1**, drop **11** has a rest diameter of approximately 6 mm. The conductor liquid **13** and the insulating liquid of drop **11** being substantially of same density, drop **12** has a hemispheric shape. When it is at rest (position A), the edge of drop **11** is at an angle of approximately 45° to the surface of chamber **12**. In its limit

position (position B), the edge of drop **11** is at an angle of approximately 90° to the surface of chamber **12**. The described device, using as a conductor liquid **13** salt water of optical index 1.35 and, for the insulating liquid of drop **11**, oil having an optical index of 1.45, achieves approximately 40 diopters of focus variation for an applied voltage of 250 volts and an electrical power of some mW. The frequency of the alternating voltage is in this case comprised between 50 and 10,000 Hz, its period being substantially smaller than the response time of the system which is several hundredths of a second.

The variable focus lens according to the present invention may have a size comprised between several tens of μm and several tens of mm, and may in particular be applied to the field of optoelectronic systems or to endoscopy.

What is claimed is:

1. A variable focus lens comprising a chamber **(12)** filled with a first liquid **(13)**, a drop of a second liquid **(11)** being disposed at rest on a region of a first surface of an insulating wall of the chamber, the first and second liquids being non miscible, of different optical indexes and of substantially same density, characterized in that:

the first liquid is conductive;

the second liquid is insulating;

in that it comprises:

means for applying a voltage between the conductor liquid and an electrode **(16; 26; 35–37; 75–79)** placed on the second surface of said wall; and

centering means for maintaining the centering of the edge of the drop while the voltage is applied and for controlling the shape thereof.

2. The variable focus lens according to claim **1**, in which the centering means allows a continuous maintaining of the centering of the drop and a continuous control of the shape of the edge of the drop while a varying voltage is applied by said means for applying a voltage.

3. The variable focus lens according to claim **2**, in which the first surface is substantially flat, the contact region **(15)** is circular and centered about an axis (O) which is perpendicular to the first surface.

4. The variable focus lens according to claim **3**, in which the centering means corresponds to a progressive thickening of the second surface of the wall of the chamber towards said axis, said electrode **(26)** being applied against said second surface.

5. The variable focus lens according to claim **3**, in which the centering means corresponds to a radial decrease of the wetting with respect to the first liquid **(13)**, towards the center of said contact region **(15)** with the second liquid.

6. The variable focus lens according to claim **3**, in which the centering means corresponds to a radial gradient of the dielectric constant of said wall of the chamber **(53)** at the level of said contact region **(15)** with the second liquid.

7. The variable focus lens according to claim **1**, in which the first surface is substantially flat, the contact region **(15)** is circular and centered about an axis (O) perpendicular to the first surface, and wherein the centering means comprises an electrode formed of one or several circular concentric strips **(35–37)** insulated from each other, centered about said axis, the circular strips being supplied by distinct voltage sources of values decreasing towards said axis.

8. The variable focus lens according to claim **1**, in which the chamber is cylindrical, the first surface is the internal surface of the chamber, the contact region with the second liquid corresponds to a cylindrical section of the chamber, the centering means is comprised of one or several cylindrical electrodes of same diameter, insulated from each other, placed side by side against the external surface of the chamber at the level of the border of said contact region, the electrodes being supplied by different voltages of values decreasing towards the center of said contact region.

9. The variable focus lens according to claim **1**, in which the first surface is substantially flat, the contact region **(15)** is rectangular and symmetric with respect to an axis (O) perpendicular to the first surface and the centering means is comprised of an electrode formed of one or several rectangular concentric strips insulated from each other, symmetric with respect to said axis (O), the rectangular strips being supplied by distinct voltage sources of decreasing values towards said axis.

10.The variable focus lens according to claim **1**, in which said wall is comprised of two non parallel planes and in which said region bridges said two planes.

* * * * *